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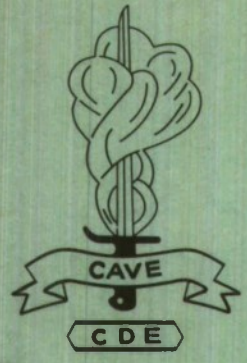
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# THE DETECTION OF DISTANT AEROSOLS AND SPRAY CLOUDS BY A LIDAR SYSTEM BASED ON THE CARBON DIOXIDE (CO<sub>2</sub>) LASER

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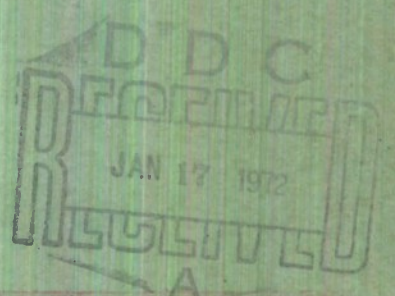
G.H.Cockett and B.R.D.Stone

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Technical Paper No. 55

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*Gp 1*

*Carbon dioxide lasers*  
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C.D.E. TECHNICAL PAPER NO.55.  
DATE: APRIL 1971

THE DETECTION OF DISTANT AEROSOLS AND SPRAY CLOUDS BY A LIDAR  
SYSTEM BASED ON THE CARBON DIOXIDE (CO<sub>2</sub>) LASER

by

G.H. Cockett and B.R.D. Stone

SUMMARY

The feasibility of the use of a CO<sub>2</sub> lidar system in various weather conditions for the detection of distant aerosols and sprays is considered, with the main emphasis on the detection of spray from high speed aircraft. A comparison is made of the known performance of the CDE ruby lidar with the performance of CO<sub>2</sub> lidars based on laser powers and detectors likely to be practicable in the immediate future.

It is concluded that the CO<sub>2</sub>/TGS lidar system would be inferior in performance to the ruby system but the CO<sub>2</sub>/PbSnTe system would appear to offer advantages in lower required power output and in higher repetition rate for the same detection range. Details are given of the technical parameters about which more reliable information is required before a more accurate appreciation of the problem can be completed.

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THE DETECTION OF DISTANT AEROSOLS AND  
SPRAY CLOUDS BY A LIDAR SYSTEM BASED ON THE  
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by

G. H. COCKETT AND B. R. D. STONE

1. INTRODUCTION

Lane et al (1966) demonstrated the ability of a lidar system based on a wavelength of 0.6943  $\mu\text{m}$  to detect the presence of low concentrations of chemical and biological aerosols in the atmosphere. Since then the CDE lidar system has consistently detected simulant CW sprays produced from high speed aircraft at ranges of up to 20 km in conditions of good visibility, and biological aerosols to approximately 11 km in the same conditions.

The detection capability of such a system based on visible radiation is a function of visibility, and analysis of the results of many experiments indicates that in practice the detection range of a system based on a 50 MW ruby laser is unlikely to be significantly greater than the prevailing visual range, as defined by the Koschmieder criterion (see 3.4).

This dependence of the detection range on visual range would be greatly reduced for a lidar system based on a carbon dioxide (CO<sub>2</sub>) laser operating at a wavelength of 10.6 $\mu\text{m}$  since not only are absorption losses minimal, as this wavelength lies at the centre of

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an atmospheric window but also because loss of radiation by scattering due to the natural atmospheric aerosol is very much less than at visible wavelengths except perhaps when the visual range is less than 1 km.

The present state of development of the CO<sub>2</sub> laser indicates that very high powers at high repetition rates are likely to be available eventually from reasonably compact systems. Thus the stage has been reached when it is worthwhile considering the application of this laser to the detection of distant chemical and biological aerosols and sprays: in this paper the question of possible identification by Raman scatter is not analysed but will be the subject of further study.

A recent paper by Lomer (1970) has provided data useful to the present analysis on the performance of CO<sub>2</sub> lasers and infra-red detectors.

2. THE LIDAR RANGE EQUATION - THEORY OF DETECTION BY LIDAR

The lidar system consists basically of a transmitter i.e. the laser, a receiver which will be a collector of backscattered radiation, and a detector to convert the radiant energy to electrical energy. For such a system the backscattered power, P<sub>R</sub> intercepted instantaneously by the receiver from an aerosol with a volume back-scattering coefficient β'<sub>180</sub> at a range R is

$$P_R = P_0 \frac{c\tau}{2} \beta'_{180} \frac{A'}{4\pi R^2} e^{-2\sigma R} \quad (1)$$

where P<sub>0</sub> is the power of the laser

A' is the area of the receiver

σ is the atmospheric extinction coefficient

c is the velocity of light

and τ is the duration of the laser pulse.

In this equation  $\frac{c\tau}{2}$  represents the depth of cloud along the axis of propagation of the laser pulse which will contribute at any instant to the received signal.

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By definition  $\beta'_{180}$ , which has units of area per unit volume, is the effective area of aerosol in unit volume of atmosphere so that the backscattered radiation may be treated as though it came from an isotropic scatterer.

It is, however, convenient in the case of relatively small chemical or biological clouds to express the received power in a slightly different form eliminating both  $\beta'_{180}$  and  $\frac{c\tau}{2}$ .

$$\text{Then } P_R = P_o e^{-2\sigma R} \frac{A'}{4\pi R^2} \frac{S_R}{S_o} \quad (2)$$

where  $S_R$  is the effective area for backscattering for the particles instantaneously illuminated at distance  $R$

and  $S_o$  is the total illuminated space at this distance.

If the laser beam divergence is  $\theta$

$$S_o = (R\theta)^2 \quad (3)$$

at a distance  $R$  for a pulse of square cross-section.

The degree of usefulness of an infra-red detector is generally given as  $D^*$ , the area normalised detectivity. From this the minimum discernible signal, MDS, i.e. the received signal in watts equal to the noise power in watts is obtained as

$$\text{MDS} = \frac{A^{\frac{1}{2}} \Delta f^{\frac{1}{2}}}{D^*} \quad (4)$$

where  $A$  is the detector area and  $\Delta f$  is the bandwidth.

Thus for a lidar system where the detectivity is limited by the detector noise

$$\text{MDS} = \frac{A^{\frac{1}{2}} \Delta f^{\frac{1}{2}}}{D^*} = P_o e^{-2\sigma R} \frac{A'}{4\pi R^2} \frac{S_R}{S_o} T' \quad (5)$$

where  $T'$  is the optical transmission of the system.

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For the purpose of calculating the laser power required to produce a signal N times the MDS the above equation may be rearranged so that the required power

$$P_o = \frac{N A^{\frac{1}{2}} \Delta f^{\frac{1}{2}} 4\pi R^2 S_o e^{2\sigma R}}{D^* \cdot A' \cdot S_R \cdot T'} \quad (6)$$

N being the signal to noise ratio.

3. FACTORS INFLUENCING SYSTEM PERFORMANCE OF LIDAR

3.1 Lasers

The rate of progress in the development of CO<sub>2</sub> lasers has been so rapid in the last year or so that it can now be assumed (Lomer 1970) that lasers with arbitrarily small beam divergence can be developed to give at least 10 J pulses with 50 MW peak powers for single shot operation or 1 MW peak powers at a frequency of a few kHz. Pulse duration is of the order of 100 ns. This is based on the performance of the new generation of atmospheric pressure CO<sub>2</sub> lasers with either static or flowing gas detailed in Table 1.

Table 1

Performance of Atmospheric Pressure CO<sub>2</sub> Lasers

Type	Performance	Comment
Static Gas	Up to 10 J/m 200 ns long pulses ~ 50 MW peak power	Lower power in single mode
High transverse gas flow	150 W mean at 1 kHz 150 m J/pulse ~ 1 MW	1 m long. Considerable improvements appear likely in the performance of this type of system.

Work on these lasers was first reported by the Defence Research Laboratories, Valcartier in Canada (e.g. Hamer 1970), and a very active programme of work has been pursued at S.E.R.L. Baldock for the last 12 months where latest results (Lamberton and Pearson 1971) of 20 J/l of excited volume are a factor of 4 better than any other known work.

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Efficiencies of 10 - 20% have been quoted.

Thus a considerable advance has been achieved over the first generation of low pressure/low flow CO<sub>2</sub> lasers, where typical Q-switched output might be 8kW/pulse/m at 1 kHz with maximum output of ~ 30 kW.

The size of the laser system required for the detection of chemical sprays will depend on the pulse repetition rate which itself is dependent on the scanning capability required. To maintain maximum power density in the beam a small beam divergence is required, but the smaller the beam divergence the greater is the repetition rate needed to maintain the same rate of area scan. A beam divergence of 0.2 m rad would produce a beam diameter of 1 m at a range of 5 km. Therefore to scan a height of 200 m at this range in, say, 2 s a pulse repetition rate of 100 pps would be required.

Single shot operation of the lidar would mean a more compact system but would almost certainly require use of a greater beam spread and a consequent increase in laser output to maintain the same detection range. In the present work a beam spread of 0.2 m radian is assumed.

It is proposed to investigate the possible benefits of the more refined systems such as a scanning/imaging facility and differential beam spreading ('fanning') at a later date.

### 3.2. Detectors

It is necessary to employ detectors which have high detectivity D\* as defined in Section 2 and fast response time. The basic types available are:-

(1) Thermal Detectors

(2) Photon Detectors

#### 3.2.1. Thermal Detectors

The only thermal device with a fast response time is a pyroelectric detector triglycine sulphate (TGS). It has one

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distinct advantage over photon detectors in that it operates at normal ambient temperatures, unlike photon detectors which need cooling. It is possible with frequency compensated amplifiers to operate at a band width of 100 MHz. In the direct mode a noise equivalent power of  $5 \times 10^{-8} \text{ W.Hz}^{\frac{1}{2}}$  in a  $10^7 \text{ Hz}$  bandwidth for a 1 mm square area corresponding to  $D^* = 2 \times 10^6 \text{ cm Hz}^{\frac{1}{2}} \text{ W}^{-1}$  is attainable.

### 3.2.2. Photon Detectors

Four types are available.

- (a) Intrinsic semi-conductors, Lead Tin Telluride (PbSnTe) and Mercury Cadmium Telluride (HgCdTe)
- (b) Extrinsic semi-conductors, Copper doped Germanium (Ge:Cu) and Mercury doped Germanium (Ge:Hg).

All these detectors require cooling to either  $77^\circ\text{K}$  for PbSnTe and HgCdTe or lower temperatures ( $4^\circ\text{K}$  for Ge:Cu and  $30^\circ\text{K}$  for Ge:Hg).

Of these photon detectors the one best suited to applications requiring high sensitivity and high speed is lead tin telluride. It operates at liquid nitrogen temperatures and typically has an area of  $2.5 \times 10^{-3} \text{ cm}^2$ , a response time in the 20 to 50 ns range and, with a  $60^\circ$  field of view, at  $10.6 \mu\text{m}$   $D^* \sim 2 \times 10^{10} \text{ W}^{-1} \text{ cm. Hz}^{\frac{1}{2}}$ ; this can be increased to approximately  $6 \times 10^{10} \text{ W}^{-1} \text{ cm.Hz}^{\frac{1}{2}}$  by decreasing the field of view but further decreases of field of view would not lead to increases in  $D^*$ . Because of difficulties in matching the low impedance of this type of detector to a low noise amplifier, the combination is limited by its own internal noise rather than the noise associated with background radiation; therefore its potential cannot be fully realised. It is hoped, however, to increase the impedance and responsivity by a factor of 20 or 30 in order to alleviate these problems.

In this assessment two detectors are considered:

- (i) Lead tin telluride with its advantage of high  $D^*$  but with its major disadvantage in its requirement for liquid nitrogen cooling.

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- (ii) Triglycine sulphate with its advantage of ambient temperature operation but with its disadvantage compared with lead tin telluride of lower D\*.

The two germanium based detectors referred to above have been omitted from this assessment because of the difficulties associated with operation at temperatures in the range 30° to 4° K. in the field.

In both cases it is assumed that a 10 to 1 signal to noise ratio is necessary for the detection of the cloud and that background noise is limited by a filter with 50% transmission at 10.6  $\mu\text{m}$ . It has been assumed also that generally the systems are limited by the noise of amplifiers and detectors; on those infrequent occasions when the atmosphere is an efficient scatterer of 10.6  $\mu\text{m}$  radiation i.e. fogs, the system may be background limited.

### 3.3. The Receiver

The receiver is assumed to have a field of view exactly matched to the area illuminated by the laser. The backscattered power intercepted by the receiver will depend on the receiver area A' for which a value of approximately 1000  $\text{cm}^2$  has been considered. It is necessary to match the receiver and detectors such that

$$\begin{aligned} \text{Area of Receiver} \times \text{Receiver Field of View} &= \text{Area of} \\ \text{Detector} \times \text{Detector Field of View.} \end{aligned} \quad (7)$$

### 3.4 Atmospheric Transmission at 10.6 $\mu\text{m}$

The transmission of radiation over an atmospheric path of length R is

$$T = e^{-\sigma R} \quad (8)$$

For detection at range R with lidar the attenuation over both the outward and return paths has to be considered.

Therefore the overall transmission

$$T = e^{-2\sigma R} \quad (9)$$

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At visible wavelengths the extinction coefficient,  $\sigma$ , is approximately equal to the atmospheric scattering coefficient,  $\sigma_s$ , and the absorption coefficient,  $\sigma_a$ , is negligible. In the visible range the relationship between visual range  $V$  and  $\sigma_s$  established by Koschmieder (1924) is approximately true,

$$\text{i.e. } \sigma_s = \frac{3.92}{V} \quad (10)$$

Thus, since by definition, at the limit of visual range the atmospheric transmission is 2% and since the radiation in the lidar application has to traverse a double path, then, at the limit of visual range with a ruby lidar system, the atmospheric transmission is reduced to approximately  $4 \times 10^{-4}$ .

At  $10.6 \mu\text{m}$ , however, the scattering losses for normal atmospheric haze are greatly reduced.  $\sigma_s$  is a function of the total scattering coefficient,  $K_s$ , which is itself a function of wavelength and particle size. Normal atmospheric haze consists of fine dust particles etc with sizes up to about  $1 \mu\text{m}$  in diameter and Figure 1 which shows  $K_s$  plotted against the ratio of particle size to wavelength illustrates clearly why scattering losses at  $10.6 \mu\text{m}$  where  $r/\lambda < 1$  are so small compared with those at the ruby laser wavelength of approximately  $0.7 \mu\text{m}$ .

Droplet radii in fogs are in the range  $0.5$  to  $80 \mu\text{m}$  so that scattering becomes an important loss factor at  $10.6 \mu\text{m}$  as well as at the shorter wavelengths.

The dependence of  $\sigma_s$  on wavelength has been expressed (Hudson 1969) as

$$\sigma_s \sim \lambda^\psi \quad (11)$$

and most workers (e.g. Middleton 1952, Curcio 1961, Elterman 1964) agree that for terrestrial haze  $\psi$  can be taken as 1.3 or less. This would suggest that the ratio between  $\sigma_s$  at  $0.6943 \mu\text{m}$  and at  $10.6 \mu\text{m}$  is about 30 to 1. In fogs however the ratio may be reduced to 2 to 1. (Arnulf, Bricard et al 1957).

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In hazes the main cause of attenuation in the infra-red is absorption by water vapour and atmospheric gases such as  $\text{CO}_2$ . It is convenient that the  $\text{CO}_2$  laser wavelength lies at the centre of the 8-13  $\mu\text{m}$  atmospheric window so that absorption is minimal.

As an example of the difference in atmospheric transmission at wavelengths of 0.7 and 10.6  $\mu\text{m}$ , consider the transmission over a 5 km path when the visual range is 5 km with a temperature of  $20^\circ\text{C}$  and 60% RH. Then at 0.7  $\mu\text{m}$  transmission by definition is about 0.02. At 10.6  $\mu\text{m}$  the transmission as determined by scattering losses is 0.89 whilst that determined by water vapour absorption will be 0.54. Thus the overall transmission at this longer wavelength is 0.48. Hence the ratio of transmission over the 5 km path at 10.6  $\mu\text{m}$  to that at 0.7  $\mu\text{m}$  is 24:1

In this assessment upper and lower limits for the attenuation coefficient at 10.6  $\mu\text{m}$  of  $0.3 \text{ km}^{-1}$  and  $0.06 \text{ km}^{-1}$  have been chosen to represent relatively clear weather conditions and the value of  $\sigma = 1.96 \text{ km}^{-1}$  is suggested to represent the beginning of fog i.e. visual range of 1 km.

It is possible, however, for the attenuation to be as much as  $200 \text{ db km}^{-1}$  in severe fog (transmission over 1 km  $\sim 10^{-20}$ ) which corresponds to  $\sigma \sim 46$  and a condition rendering the use of a lidar system of very doubtful value. On the average, the attenuation is said to be about  $10 \text{ db km}^{-1}$  per mg of liquid water/ $\text{m}^3$  which would agree with the assumption that for visual range of 1 km,  $\sigma \sim 2$ .

### 3.5. Backscatter of 10.6 $\mu\text{m}$ Radiation by Chemical and Biological Sprays

The degree of backscatter from the laser radiation incident on the cloud of particles is a most important factor contributing to the ease of detection of the spray cloud but its magnitude cannot be predicted with great certainty. When particles are very much smaller in diameter than the wavelength the backscatter is inversely proportional to the fourth power of the wavelength and proportional to the sixth power of the diameter according to Rayleigh scattering. For particles approximately equal in size to or greater than the wavelength the backscatter must be calculated

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using the theory of Mie (1908). The relationship between backscatter and wavelength then becomes extremely complex. This is illustrated in Figure 2 by two graphs in which the normalised backscattering cross-section,  $\beta$ , of dielectric spheres is plotted against the size parameter,  $\alpha$ , which is equal to  $2\pi r/\lambda$ . Here  $r$  is the radius of the particle and  $\lambda$  the wavelength of the incident radiation. The first graph shows the relationship for water droplets (refractive index 1.33) and the second for a typical organic material (refractive index 1.45).  $\beta$  by definition is the gain in the backscatter over the isotropic scatter of a particle with cross-section  $\pi r^2$ .

Thus

$$\beta = \frac{1}{\pi r^2} \cdot 4\pi R^2 \cdot \frac{I_{180}}{I_0} \quad (12)$$

Where  $I_0$  is the intensity of the radiation incident at the particle and  $I_{180}$  is the intensity of backscatter detected at range  $R$ . The oscillation of the curves continues to very large values of  $\alpha$  (Kerker 1969) (unlike the case for total scatter,  $K_s$ ), but eventually with increasing  $\alpha$  the backscatter decreases, falling to a value predicted by purely geometric scattering considerations.  $\beta$  may then take the value of 0.1 or even less depending on the refractive index of the material in question, and the rate at which this value is approached depends on the refractive index and degree of absorption.

There is no clear indication in the literature of the minimum value of  $\alpha$  for which geometric considerations only may be employed in calculating  $\beta$ . However, the results of computations based on Mie theory by Fahlen and Bryant (1968) for water droplets and, more recently by C.D.E. for two cases of spheres with refractive index 1.33 and 1.45 suggest that the average value of  $\beta$  remains constant over a range of  $\alpha$  from at least 10 to 3,000, if there is no absorption.

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It is obvious that the backscatter of monochromatic radiation by clouds with a narrow size spectrum will be strongly dependent on the size. However for clouds with a fairly wide range of particle size (providing  $r > \lambda$ ) the backscatter will be approximately proportional to the total cross-sectional area of the particles forming the cloud since  $\beta$  will then be effectively constant over a wide range of  $\alpha$ .

The magnitude of  $\beta$  is a function of refractive index ( $M$ ), increasing initially, but decreasing for  $M > 2$  (Kerker 1969), such that the ratio of backscattering cross-section at  $M = 2$  to that at  $M = 1.33$  is about 5 to 1. Although the values of refractive indices of chemical agents are known in the visible spectrum no data appears to be available for the far infra-red. For water  $M$  is very different at microwave frequencies from its value in the visible spectrum, but, on the other hand, for ice the change is small. Carlon (1969) showed that apart from anomalous dispersion in the region of absorption bands the refractive index of polyethylene changes very little from 3 to 15  $\mu\text{m}$ . It is therefore assumed in this study, in the absence of evidence to the contrary, that the refractive index of typical CW aerosols is the same at 10.6  $\mu\text{m}$  as at 0.5  $\mu\text{m}$  (i.e. approximately 1.45). The effect of the possible absorption of 10.6  $\mu\text{m}$  radiation by the spray is dealt with in Appendix A.

The particle diameter of the aircraft bacterial spray or fine chemical spray which is required to be windborne over large distances is likely to be of the order of a few micrometres; the mass median diameter of a simulant cloud detected at 11 km range by the 0.6943  $\mu\text{m}$  ruby lidar was about 3  $\mu\text{m}$  in its dry state. On the other hand a typical mass median diameter of a coarser aircraft chemical spray may be 300  $\mu\text{m}$  with a range extending from 100  $\mu\text{m}$  to 600  $\mu\text{m}$ , while airburst weapons may produce a dispersion where the largest sizes are up to 5 mm in diameter.

Thus it is clear that the fine bacterial spray will backscatter the visible radiation far more efficiently than the infra-red radiation, perhaps by an order of magnitude; the 300  $\mu\text{m}$  chemical spray will probably scatter both wavelengths equally efficiently, whilst if there is any difference with the large droplets of chemical rain the more likely result is for preferential

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scattering of the infra-red radiation.

The backscattering cross-section of a coarse aircraft spray has been estimated from particle size distributions obtained by Collins (1968) in investigations into the performance of a spray of involatile liquid from tanks carried by a Hunter Mk 9 aircraft. Although in these experiments sampling was carried out at ground level it is thought that the results give a reasonably accurate indication of the characteristics of the spray in the wake of the aircraft, after the initial period of break up (less than 1 s) has passed, for speeds up to approximately 400 knot [ $\approx 206 \text{ m s}^{-1}$ , (1 knot =  $0.514 \text{ m s}^{-1}$ )].

For an aircraft speed of  $129 \text{ m s}^{-1}$  and rate of spray of 8 gallons  $\text{s}^{-1}$  [ $\approx 36 \text{ l s}^{-1}$ , (1 gallon  $\text{s}^{-1} = 4.5 \text{ l s}^{-1}$ )] the concentration of spray in a line source would be  $283 \text{ ml m}^{-1}$ . From the data on size distribution it is estimated that the total cross-sectional area of the spray would be approximately  $1.4 \times 10^4 \text{ cm}^2 \text{ m}^{-1}$ ; or  $9 \times 10^3 \text{ cm}^2 \text{ m}^{-1}$  for an aircraft speed of  $206 \text{ m s}^{-1}$ , the case considered here.

As a first approximation it is assumed that the normalised backscattering cross-section  $\beta$ , of the particles forming the cloud is unity. Thus the maximum area of the spray available for backscatter is  $9 \times 10^3 \text{ cm}^2 \text{ m}^{-1}$ . This represents the highest degree of backscatter likely for this particular cloud but, in order to allow for a case approaching geometric scatter, a value of  $\beta = 0.1$  is also considered briefly in this assessment and the two cases are compared.

The laser pulse at any instant in time illuminates a discrete volume in space and the signal instantaneously received by the detector will correspond to the scatter from particles within a volume defined by the product of the cross-sectional area of the laser pulse at the interception range,  $R$ , and the pulse half length,  $c\tau/2$ . In the simplest case of a pulse of square cross section, a volume,  $V$ , which is a function of range is illuminated such that

$$V = (R\theta)^2 c\tau/2, \quad (13)$$

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and the interception of this volume with the volume occupied by the spray will determine the fraction of the maximum backscatter area of the spray droplets which is able to contribute to the lidar signal at any instant.

Thus, the instantaneous backscattering cross-section of the spray cloud is a function of range, pulse length and beam divergence and must be considered in three dimensions,

- (a) along the axis of the spray cloud
- (b) at right angles to the axis of the spray cloud in the horizontal plane i.e. along the axis of propagation of the laser pulse.
- (c) at right angles to the axis of the spray cloud in the vertical plane i.e. perpendicular to the axis of propagation of the laser pulse in the vertical plane.

For (a) The maximum area available in this dimension will be  $9 \times 10^3 \times (R\theta)^2 \text{ cm}^2$  if R is measured in km and  $\theta$  in m rad

(b) Along the axis of propagation of a laser pulse of not less than 100 nsec duration the effective depth of cloud illuminated will be not less than 15m. It therefore seems reasonable to assume that in this dimension every particle along the axis will contribute instantaneously to the backscatter in the early stages of development of the cloud.

(c) Even at 10 km range the diameter of the laser pulse of beam divergence 0.2 m rad considered in this assessment will be only 2 m. It is impracticable to assume that all the available particles in the vertical plane can be illuminated by a single pulse so allowance for this factor has been made in this study by assuming:

- (i) that the change of concentration with distance from the centre of the spray is a Gaussian distribution in the early stages

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(ii) in a time long enough to allow interception of the cloud by the laser the concentration is 10% of that at the centre at a distance of  $\pm 7.5$  m in the vertical plane.

(iii) that the laser in this time intercepts the axis of the cloud.

In the present work the treatment has been confined to this single case of the aircraft spray.

#### 4. RESULTS OF ASSESSMENT

Figure 3 shows the variation with range of the peak output required from the laser for detection of an aircraft spray produced at a rate of  $36 \text{ l s}^{-1}$  for 3 different values of atmospheric extinction coefficient. The detector considered in this case was lead tin telluride. Figure 4 shows a similar relationship for the triglycine sulphate detector. The highest power output levels so far achieved with  $\text{CO}_2$  lasers are also indicated on each graph.

Figure 5 shows the effect of a variation of 10 times in the backscattering cross-section of the spray cloud on the laser power required for detection for the case of the PbSnTe detector.

#### 5. DISCUSSION

Figures 3 and 4 illustrate the wide range within which the output power of the  $\text{CO}_2$  laser may lie in meeting the various conditions covered by this analysis. For example if the aircraft spray were to be detected at ranges of 5 and 20 km in good visibility with the  $\text{CO}_2$ /TGS system, peak powers of at least 100 MW and 10GW respectively would be required. With the  $\text{CO}_2$ /PbSnTe system peak powers of only about 2 kW and 0.2 MW would be needed for detection at the same ranges in good visibility, but even in this latter case detection at 3 km in conditions of poor visibility (e.g. 1 km) would require a peak power of approximately 50 MW.

Figures 3 and 4 represent the most likely minimum values of the required laser power for PbSnTe and TGS detectors. Figure 5 however, also takes account of the fact that the backscattering



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cross-section of the cloud may be only one-tenth of that assumed for the former cases and shows curves covering both values of  $\beta$ . It illustrates also that although the required power for detection at a given range is inversely proportional to the backscattering cross-section of the cloud the influence of this change in  $\beta$  on detection range depends on the prevailing visibility and is much smaller in magnitude. For example, in this case the greatest effect of a 10 to 1 variation in backscatter results in a maximum variation of only 2 to 1 in detection range; this is for the case of good visibility. Thus the sensitivity of the detection range to errors made in the values assumed for  $\beta$  is not great.

This paper would not be complete without some attempt to compare the performance of CO<sub>2</sub> and ruby lidars. Some difficulty is experienced however, in making a precise comparison. This is partly because it has been found from experiments conducted at CDE, that the limitation of ruby lidar performance is due to either the noise level of the backscattered signal, arising from the passage of the laser pulse through the natural atmosphere, or the noise level of the solar radiation scattered into the system; these levels can only satisfactorily be determined by experiment. It is thought however, that because of the poor scattering qualities of atmospheric haze at 10.6  $\mu$ m, the practical limit of the CO<sub>2</sub> system will be imposed by detector and amplifier noise.

If the same background limited detector could be used for both CO<sub>2</sub> and ruby systems, then it has been estimated by Rensch and Long (1970) that a laser ranging system would have a received-signal to noise ratio dependence of  $1/\lambda^3$  for a target whose backscattering cross-section was independent of wavelength, the noise in this case being the backscatter signal produced by the natural atmosphere. Thus the ratio of CO<sub>2</sub> lidar to ruby lidar signal-to-noise ratios would be approximately  $(10.6/0.7)^3 = 3,500:1$ .

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Figures 3 and 4 show the dependence of the required power on the type of detector used and the basis of the comparison has therefore consisted of the predictions given by these figures and the practical CDE ruby lidar system. Even here there is a difficulty unless some statistical correlation can be found between infrared and visible extinction coefficients. However, it is certain that for almost all occasions (Arnulf and Bricard 1957) the extinction coefficient at  $10.6 \mu\text{m}$  will be a factor of at least 2 less than that at  $0.7 \mu\text{m}$ .

These difficulties and uncertainties associated with the values of certain other parameters have limited the analysis undertaken here and further information on all the following points must become available before conclusions can be presented with complete confidence;

- (i) the refractive index of organic materials at a wavelength of  $10.6 \mu\text{m}$
- (ii) the effects of absorption bands of practical materials on backscatter
- (iii) computations of normalised backscattering cross-section for large  $\alpha$  values
- (iv) atmospheric backscatter at  $10.6 \mu\text{m}$
- (v) statistical data on the day to day variation of the atmospheric extinction coefficient at  $10.6 \mu\text{m}$ , ( $\sigma_{10.6\mu\text{m}}$ ).

6. CONCLUSIONS

Because the aircraft spray considered in this paper is typical of one aspect of the CW threat and since much experimental work has already been done using this system to establish the likely performance of the ruby lidar, the detection of this aircraft spray is taken here as the criterion on which the following conclusions are based:-

- (1) The 50 MW  $\text{CO}_2$ /TGS lidar could only be used for detection at short ranges i.e., less than 5km in all weather conditions. Thus this system would be inferior to the present 50MW ruby lidar which has a detection range approximately equal to the visual range over a fairly wide visibility spectrum.



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- (2) The 1MW CO<sub>2</sub>/PbSnTe lidar operating at a frequency of 1kHz would appear to have at least as good a range capability as the ruby lidar but offers the significant advantage of a scanning/imaging facility or the possibility of a 'fanned' type of scan (cf 3.1).
- (3) The 50MW single shot CO<sub>2</sub>/PbSnTe lidar offers a marked improvement over the ruby system e.g., a 4 times gain in detection range under poor visibility conditions

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Prof. R. H. Ottewill and Dr. E. J. Moss of Bristol University are thanked for carrying out computer calculations of normalised backscattering cross-sections, and Dr. D. C. Tyte of S.E.R.L. for advice and suggestions relating, in particular, to the present status of CO<sub>2</sub> lasers and infra red detectors.

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20.



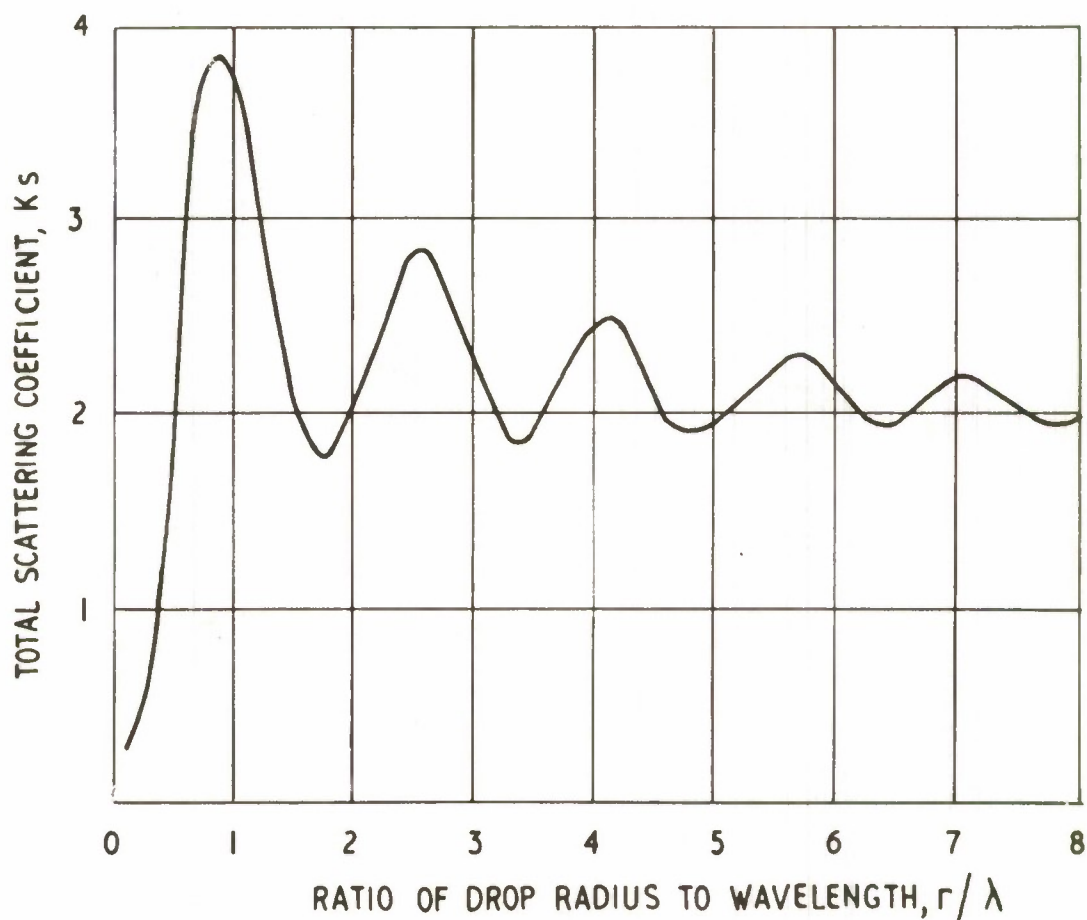
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APPENDIX A

The Effect of Absorption Bands

The study has been limited by the lack of data on the optical properties of organic materials at a wavelength of 10.6  $\mu\text{m}$ ; it has been assumed throughout, that chemical sprays are pure scatterers of radiation. In practice, a lidar may be required to detect non-volatile nerve agents, such as VX, which have a characteristic absorption band at 9.6  $\mu\text{m}$ . In many cases also, compounds of this type exhibit quite strong absorption in the region of 10.6  $\mu\text{m}$  and in some cases, the absorption peak is actually at this wavelength. Such an effect could nullify the predictions made in this paper and render the use of a  $\text{CO}_2$  lidar impracticable in this application. On the other hand, absorption at 10.6  $\mu\text{m}$  might produce a resonance effect causing re-emission at a characteristic band; providing not only a means of detection but also identification. If, alternatively, it were possible to operate two  $\text{CO}_2$  lidars with one tuned to a non-absorbed reference wavelength, and the other tuned to an absorption band, comparison of the return signal would also provide a means of identification of the aerosol. Such possibilities could only be satisfactorily investigated by experimental work with a  $\text{CO}_2$  lidar.

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RELATIONSHIP BETWEEN THE TOTAL SCATTERING COEFFICIENT,  $K_s$  & THE RATIO OF DROP RADIUS TO WAVELENGTH,  $r/\lambda$  FOR WATER DROPLETS (AFTER HOUGHTON & CHALKER, 1949)

FIG. I.



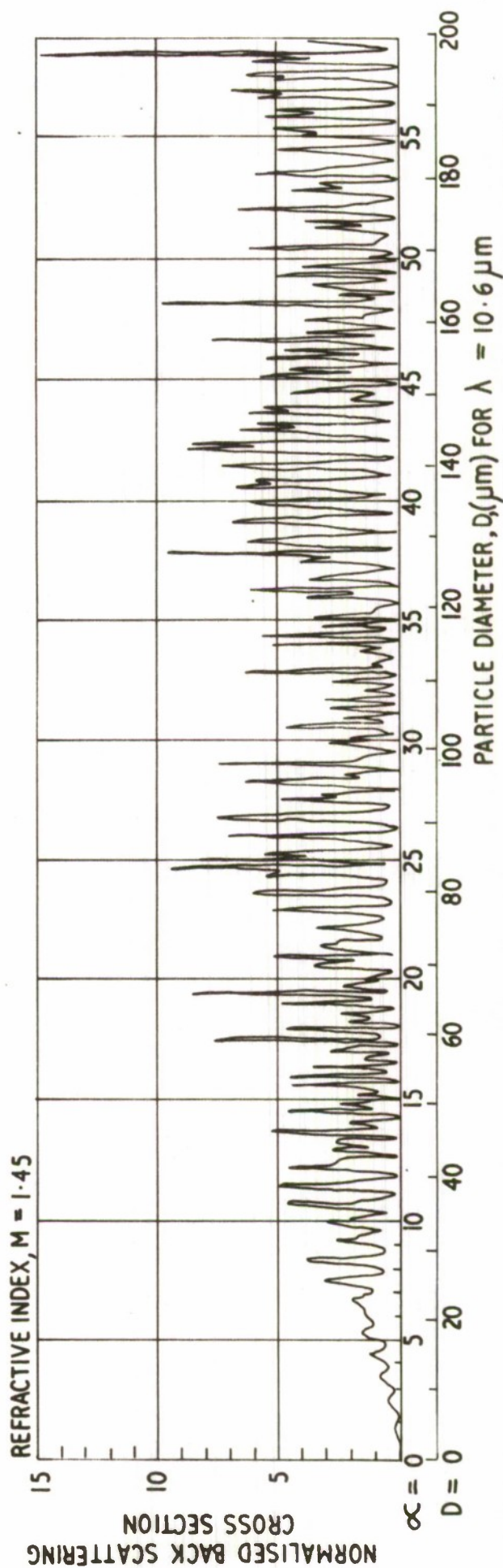
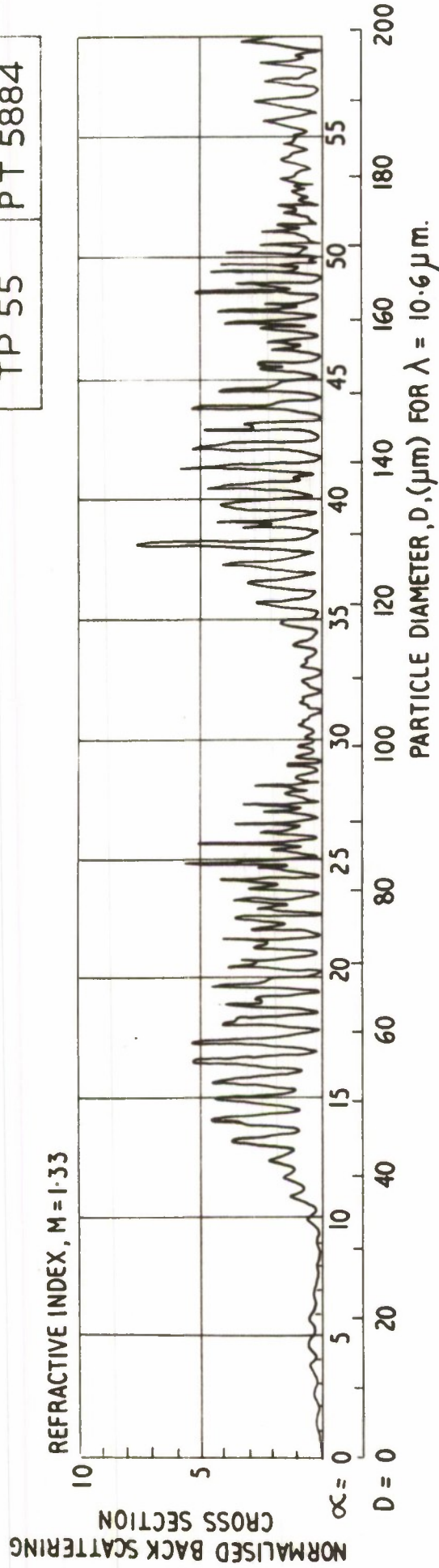


FIG. 2. RELATIONSHIP BETWEEN BACK - SCATTERING CROSS SECTION & PARTICLE SIZE.

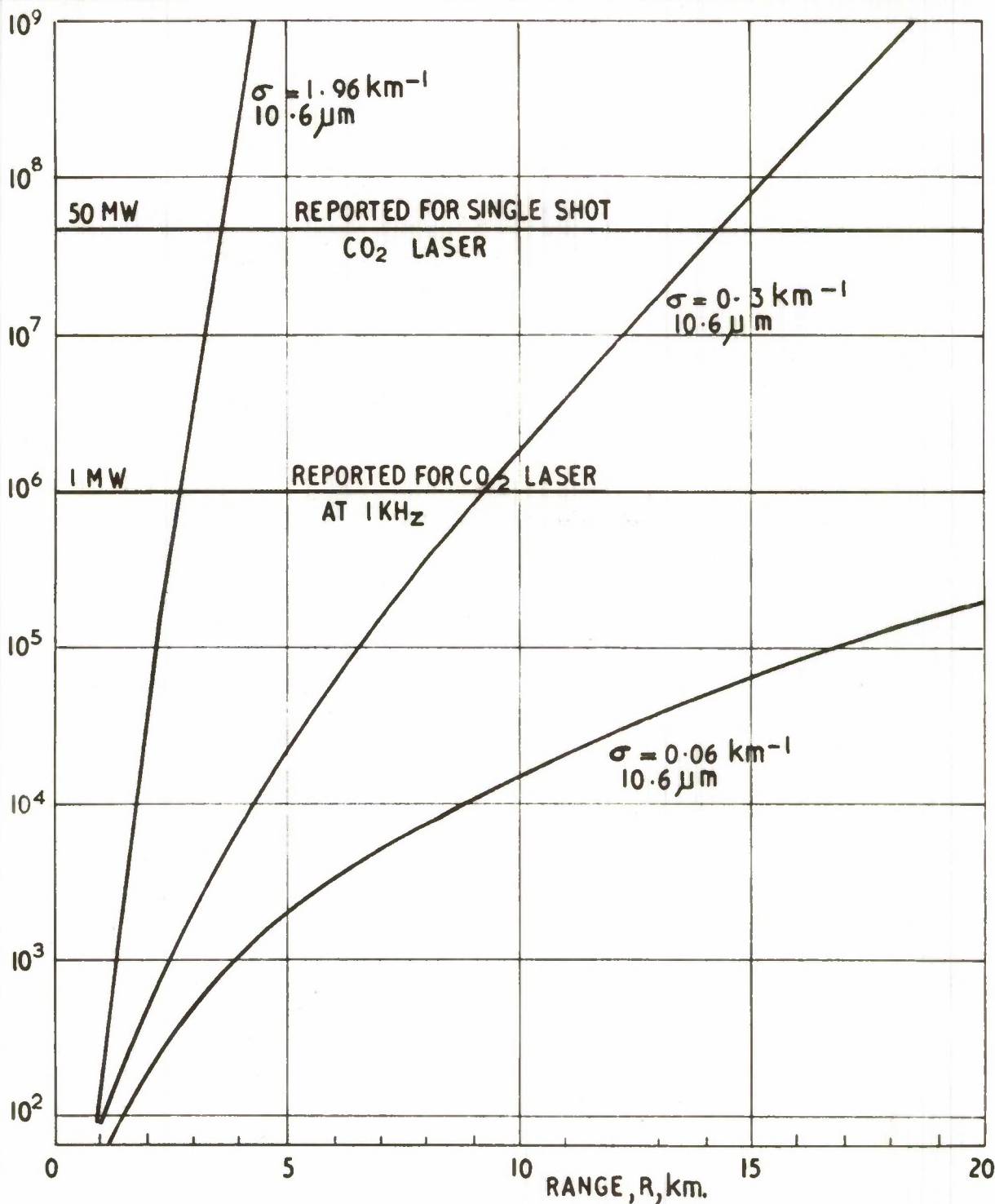
TP55 PT 5885

# SYSTEM PARAMETERS

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LIDAR		SPRAY
LASER : CO <sub>2</sub> : $\lambda = 10.6 \mu\text{m}$	DETECTOR : PbSnTe (77° K)	LINE SOURCE
BEAM DIVERGENCE = 0.2 mrad	$D^* = 6 \times 10^{10} \text{ cm} \cdot \text{Hz}^{1/2} \text{ W}^{-1}$	M.M.D. = 300 $\mu\text{m}$
PULSE DURATION $\leq 100 \text{ ns}$	$\Delta f = 10^7 \text{ Hz}$	MAX. SCATTER AREA = 9000 $\text{cm}^2 \text{ m}^{-1}$
RECEIVER DIAMETER = 30 cm	DETECTOR AREA = $6 \times 10^{-4} \text{ cm}^2$	WIDTH = 15 m
S/N RATIO = 10 : 1		REFRACTIVE INDEX $\sim 1.4 + 0i$

REQUIRED LASER PEAK POWER, P<sub>0</sub>, WATTS



REQUIRED LASER POWER v RANGE FOR DETECTION BY 'CO<sub>2</sub> LIDAR' WITH PbSnTe DETECTOR FOR VARIOUS VALUES OF EXTINCTION COEFFICIENT,  $\sigma$ .

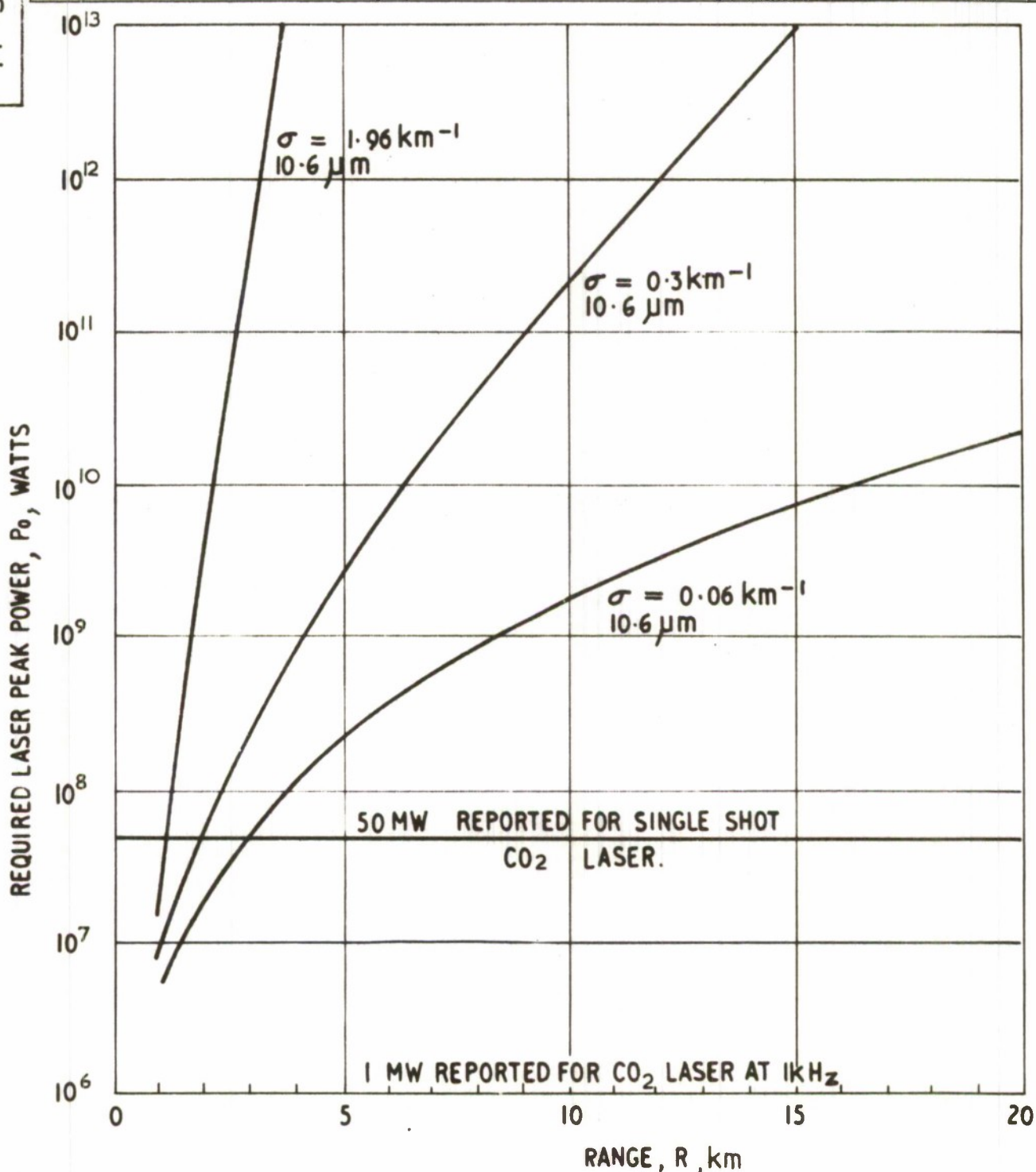
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FIG.3.



SYSTEM PARAMETERS

LIDAR		SPRAY
LASER: CO <sub>2</sub> : $\lambda = 10.6 \mu\text{m}$	DETECTOR: TGS (20°C)	LINE SOURCE
BEAM DIVERGENCE = 0.2 mrad	$D^* = 2 \times 10^6 \text{ cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$	M.M.D. 300 $\mu\text{m}$
PULSE DURATION $\leq 100 \text{ ns}$	$\Delta f = 10^7 \text{ Hz}$	MAX SCATTER AREA = 9000 $\text{cm}^2 \cdot \text{m}^{-1}$
RECEIVER DIAMETER = 30 cm	DETECTOR AREA = $10^{-2} \text{ cm}^2$	WIDTH = 15 m
S/N RATIO = 10:1		REFRACTIVE INDEX $\sim 1.4 + 0i$



REQUIRED LASER POWER v RANGE FOR DETECTION BY 'CO<sub>2</sub> LIDAR' WITH TGS DETECTOR FOR VARIOUS VALUES OF EXTINCTION COEFFICIENT,  $\sigma$

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TP 55 PT 5887

LIDAR PARAMETERS : AS FOR FIGURE 3.

SPRAY : LINE SOURCE

WIDTH = 15 m

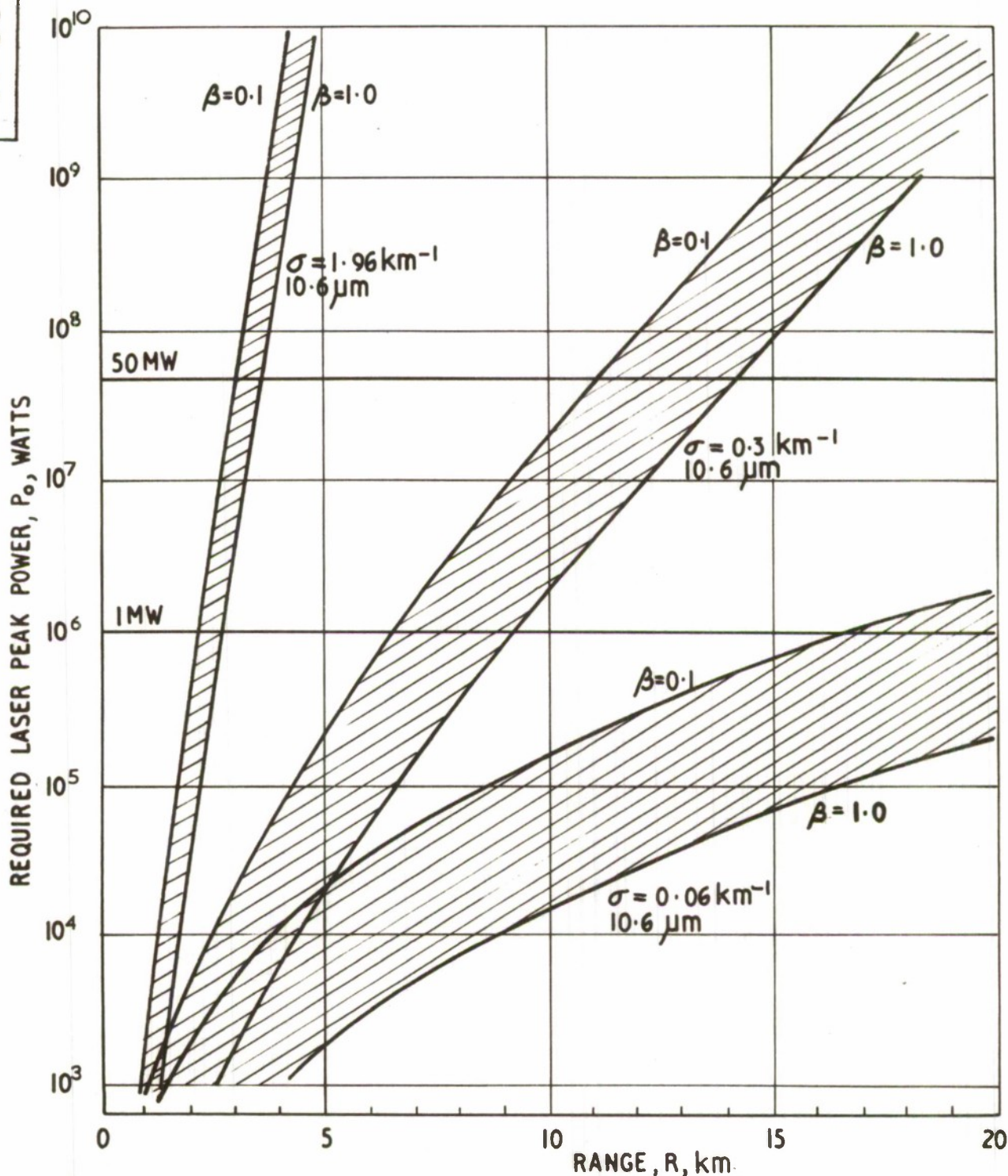
REFRACTIVE INDEX  $\sim 1.4 + 0i$

MAX. SCATTER AREA (i)  $9000 \text{ cm}^2 \text{ m}^{-1}$

(ii)  $900 \text{ cm}^2 \text{ m}^{-1}$

$\beta = 1.0$

$\beta = 0.1$



COMPARISON OF REQUIRED LASER POWERS (FOR  $\text{PbSnTe}$  DETECTOR) FOR A VARIATION OF  $10 \times$  IN BACK SCATTERING CROSS SECTION OF CLOUD.

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FIG.5.



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